A DETERMINISTIC FREQUENCY HOPPING RAYLEIGH FADING CHANNEL SIMULATOR DESIGNED BY USING OPTIMIZATION TECHNIQUES

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Abstract - A channel simulator that models accurately the physical channel statistics determined by the frequency separation between two carriers in frequency hopping (FH) systems is called a FH channel simulator. In this paper, we propose a novel deterministic FH simulation model for Rayleigh fading channels, which can easily be implemented and is very useful for investigating the frequency diversity gain of low speed mobiles in practical FH systems. The optimization technique based on the L_p-norm method is exploited to calculate some simulation model parameters. Moreover, the performance evaluation of the proposed channel simulator is performed for typical GSM FH mobile radio data transmission scenarios. A pretty good agreement between the statistical properties of the simulation model and those of the underlying analytical model is observed in all cases.

Keywords - Deterministic channel modeling, Rayleigh fading channels, frequency hopping, optimization techniques, statistics.

I. INTRODUCTION

Frequency hopping (FH) is one of the many techniques that are being considered to improve the system performance and spectral efficiency of modern wireless communication networks by providing frequency diversity and interference diversity. The use of FH in GSM is the most popular FH application in cellular systems [1]–[5]. Many contributions have also applied FH to spread spectrum multiple access (SSMA) communication systems [6]–[8] and Bluetooth wireless networks [9].

It is typically assumed in FH systems that the separation of hopping frequency bands is larger than the coherence bandwidth and, hence, the received signals are uncorrelated [3, 4, 10]. However, such an assumption is not generally true since channel correlation within coherence bandwidth usually occurs in practical FH systems [7, 11]. Therefore, it is of great significance to investigate the correlation properties of the received signals at different carrier frequencies, which might be very helpful to set up the frequency hop size guaranteeing quasi uncorrelated fading and therefore higher frequency diversity gain in real cellular systems employing FH.

For the design and implementation of a FH wireless communication system, it is essential to have a channel simulator which can be realizable in laboratory to duplicate the assumed statistical properties, thus, make it possible for the performance analysis, optimization and test. The resulting channel simulator that models accurately the physical channel statistics determined by the frequency separation between two carriers in FH systems is called a FH channel simulator. Only several papers have contributed to this topic. A frequency domain channel model with FH capabilities has been developed by using frequency transform techniques in [12]. A method of modeling frequency correlation of fast fading which can be used to emulate FH in a wide-band channel has been described in [13]. A stochastic FH simulation model for Rayleigh fading channels has been presented in our previous paper [14]. This model enables the statistical fitting to a physical channel model with high precision, but its complexity is high due to the stochastic property and the used double sum of sinusoids.

In this paper, we propose a novel FH Rayleigh fading channel simulator based on Rice's sum of sinusoids [15, 16]. Due to its deterministic feature and the used single sum of sinusoids, this model can easily be implemented with low complexity. The adjustments of model parameters are performed numerically by using an optimization technique based on the L_p-norm method.

II. FH ANALYTICAL MODEL

In this section, we discuss the theoretical analytical model and its correlation properties, which is very important for the performance evaluation of our deterministic simulation model presented in Section V. The equivalent complex baseband notation will be used throughout the paper.

Under narrow-band conditions, the widely accepted model is the Rayleigh fading channel model, where it is assumed that no line-of-sight path exists between the base station and mobile station antennas. We start by

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writing the envelope of the received signals at two different carrier frequencies, denoted by f_c and f'_c, which can be regarded as two frequencies in the frequency list determined by the FH pattern, in terms of narrow-band inphase and quadrature components:

$$\zeta(t) = |\mu_1(t) + j\mu_2(t)| \text{ , at } f_c \text{ ,} \quad (1a)$$

$$\zeta'(t) = |\mu'_1(t) + j\mu'_2(t)| \text{ , at } f'_c \text{ ,} \quad (1b)$$

where both $\mu_i(t)$ and $\mu'_i(t)$ $(i = 1, 2)$ are real Gaussian noise processes, each with zero mean and variance σ_0^2. As a prerequisite of Rayleigh process, $\mu_1(t)$ $(\mu'_1(t))$ and $\mu_2(t)$ $(\mu'_2(t))$ are statistically independent, and thus, they are uncorrelated stochastic processes.

If two signals are transmitted from the base station at different carrier frequencies, then, their statistical properties, observed at the mobile antenna, are uncorrelated if the absolute value of the frequency separation $\chi = f'_c - f_c$ is sufficiently large. To answer the question of how large is enough for the frequency separation between two carriers, which can be employed to set up the frequency hop size in real FH systems, we have to study in detail the following autocorrelation functions (ACFs) and cross-correlation functions (CCFs):

$$r_{\mu_i\mu_j}(\tau) := E\{\mu_i(t)\mu_j(t+\tau)\} \text{ ,} \quad (2a)$$

$$r_{\mu_i\mu'_j}(\tau, \chi) := E\{\mu_i(t)\mu'_j(t+\tau)\} \text{ ,} \quad (2b)$$

for all $i = 1, 2$ and $j = 1, 2$, where the operator $E\{\cdot\}$ refers to a statistical average. All of these correlation functions can be derived provided that the horizontal directivity pattern of the receiving antenna and the distributions of the angles of arrival and the echo delays are known [17]. Without much loss of generality, we assume that the omnidirectional antenna is deployed, the angles of arrival are uniformly distributed, and the echo delays τ' are negative exponentially distributed according to the following expression:

$$p(\tau') = \frac{1}{\alpha} e^{-\frac{\tau'}{\alpha}} \text{ ,} \quad (3)$$

where α represents the delay spread. The value of α is 0.1086 μs under the rural area (RA) environment [18], which implies a frequency-nonselective channel for GSM. It then follows from these assumptions that the expressions (2a) and (2b) can be solved analytically [16]:

$$r_{\mu_i\mu_i}(\tau) = r_{\mu'_i\mu'_i}(\tau) = \sigma_0^2 J_0(2\pi f_{max}\tau) \text{ ,} \quad (4a)$$

$$r_{\mu_1\mu_2}(\tau) = r_{\mu'_1\mu'_2}(\tau) = 0 \text{ ,} \quad (4b)$$

$$r_{\mu_i\mu'_i}(\tau, \chi) = \frac{\sigma_0^2 J_0(2\pi f_{max}\tau)}{1 + (2\pi\alpha\chi)^2} \text{ ,} \quad (4c)$$

$$r_{\mu_1\mu'_2}(\tau, \chi) = -r_{\mu_2\mu'_1}(\tau, \chi) = -2\pi\alpha\chi r_{\mu_1\mu'_1}(\tau, \chi) \text{ ,} \quad (4d)$$

where $i = 1, 2$. In (4a) and (4c), f_{max} is the maximum Doppler frequency, and $J_0(.)$ denotes the zeroth-order Bessel function of the first kind. Note that the variance of $\mu_i(t)$ can easily be obtained by evaluating (4a) at $\tau = 0$, i.e., $r_{\mu_i\mu_i}(0) = \sigma_0^2$. The uncorrelatedness between the inphase and quadrature components is shown in (4b). Close observation of (4c) and (4d) indicates that $r_{\mu_i\mu'_i}(\tau, \chi)$ is an even function, while $r_{\mu_1\mu'_2}(\tau, \chi)$ is an odd function with respect to the frequency separation χ, i.e., $r_{\mu_i\mu'_i}(\tau, \chi) = r_{\mu_i\mu'_i}(\tau, -\chi)$ and $r_{\mu_1\mu'_2}(\tau, \chi) = -r_{\mu_1\mu'_2}(\tau, -\chi)$. When $\chi = 0$, which implies the non-hopping case, the expressions (4c) and (4d) will reduce to (4a) and (4b), respectively. Hence, $r_{\mu_i\mu'_i}(\tau, 0) = r_{\mu_i\mu_i}(\tau)$ and $r_{\mu_1\mu'_2}(\tau, 0) = r_{\mu_1\mu_2}(\tau)$. Equation (4c) also states that the correlation between the inphase components of two received signals having different frequencies decreases with the increasing absolute value of frequency separation χ, as one would expect. This statement also holds for (4d) when χ is sufficiently large. When we analyze these two equations on the condition of FH, i.e., $\chi \neq 0$, it is clear that the strongest correlation of two signals occurs if there is no time delay ($\tau = 0$). In order to ensure that we can find the proper value of frequency separation which is somehow large compared to the coherence bandwidth of the channel, we must investigate (4c) and (4d) at $\tau = 0$. Note that the expressions (4a)–(4d) will form the basis for the statistical analysis to follow in succeeding sections of this paper and the preceding analysis is of great importance for the optimization procedure in Section IV.

III. DETERMINISTIC FH SIMULATION MODEL

In this section, we will propose a novel deterministic FH Rayleigh fading channel simulator that can faithfully simulate all those correlation properties of the underlying analytical model in order to study FH systems in the laboratory. By applying the principle of deterministic channel modeling [19, 20], we can model the real Gaussian noise processes $\mu_i(t)$ and $\mu'_i(t)$ $(i = 1, 2)$ by a finite sum of properly weighted sinusoids:

$$\tilde{\mu}_1(t) = \sum_{n=1}^{N} c_n \cos(2\pi f_n t + \theta_n) \text{ ,} \quad (5a)$$

$$\tilde{\mu}_2(t) = -\sum_{n=1}^{N} c_n \sin(2\pi f_n t + \theta_n) \text{ ,} \quad (5b)$$

$$\tilde{\mu}'_1(t) = \sum_{n=1}^{N} c_n \cos(2\pi f_n t + \theta'_n) \text{ ,} \quad (5c)$$

$$\tilde{\mu}'_2(t) = -\sum_{n=1}^{N} c_n \sin(2\pi f_n t + \theta'_n) \text{ ,} \quad (5d)$$

where N represents the number of sinusoids, mainly determining the realization expenditure and the performance of the resulting channel simulator. The other three model parameters, i.e., the Doppler coefficients c_n, the discrete Doppler frequencies f_n, and the phases θ_n (θ_n'), will dominate how well the statistical properties of our simulation model can approximate those of the analytical model. It is worth mentioning that all these parameters will be determined during the simulation setup phase and kept constant during the simulation run. Thus, the resulting simulator is of the deterministic property. In order to get the optimal approximation of the probability density function (PDF) of the deterministic process $\tilde{\mu}_i(t)$ to the ideal Gaussian PDF of the stochastic process $\mu_i(t)$ for a given number N, the Doppler coefficients c_n have to be calculated according to the following closed-form expression [19]:

$$c_n = \sigma_0 \sqrt{\frac{2}{N}} \, . \tag{6}$$

In (5), the Doppler phases θ_n and θ_n' are related to the carrier frequencies f_c and $f_c' = f_c + \chi$, respectively. In other words, the occurrence of a frequency hop $f_c \to f_c'$ in the physical channel model corresponds to phase hops $\theta_n \to \theta_n'$ in our simulation model, whereas the other parameters remain unchanged. Therefore, we propose to express them as follows

$$\theta_n = 2\pi f_c \varphi_n \, , \qquad \theta_n' = 2\pi (f_c + \chi) \varphi_n \, , \tag{7a,b}$$

where φ_n is a quantity, which will be determined, together with f_n, by using optimization techniques in the forthcoming section.

Due to the deterministic feature of our simulation model, the correlation properties, i.e., the counter parts of (2a) and (2b), have to be calculated by applying time averages according to the following definitions:

$$\tilde{r}_{\mu_i \mu_j}(\tau) := \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \tilde{\mu}_i(t) \tilde{\mu}_j(t+\tau) dt \, , \tag{8a}$$

$$\tilde{r}_{\mu_i \mu_j'}(\tau, \chi) := \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \tilde{\mu}_i(t) \tilde{\mu}_j'(t+\tau) dt \, , \tag{8b}$$

for all $i, j = 1, 2$. Performing the substitutions (5a)–(5d) in (8a) and (8b), the following expressions can immediately be obtained:

$$\tilde{r}_{\mu_i \mu_i}(\tau) = \tilde{r}_{\mu_i' \mu_i'}(\tau) = \sum_{n=1}^{N} \frac{c_n^2}{2} \cos(2\pi f_n \tau) \, , \tag{9a}$$

$$\tilde{r}_{\mu_1 \mu_2}(\tau) = \tilde{r}_{\mu_1' \mu_2'}(\tau) = -\sum_{n=1}^{N} \frac{c_n^2}{2} \sin(2\pi f_n \tau) \, , \tag{9b}$$

$$\tilde{r}_{\mu_i \mu_i'}(\tau, \chi) = \sum_{n=1}^{N} \frac{c_n^2}{2} \cos(2\pi f_n \tau + 2\pi \varphi_n \chi) \, , \tag{9c}$$

$$\tilde{r}_{\mu_1 \mu_2'}(\tau, \chi) = -\tilde{r}_{\mu_2 \mu_1'}(\tau, \chi) = -\sum_{n=1}^{N} \frac{c_n^2}{2} \sin(2\pi f_n \tau + 2\pi \varphi_n \chi) \, , \tag{9d}$$

These equations show us again that the good agreement between (9a)–(9d) and (5a)–(5d) strongly relies on the simulation model parameters. Since c_n has been determined by (6), we will proceed further to find appropriate values for f_n and φ_n.

IV. OPTIMIZATION TECHNIQUES

In this section, we will focus on the optimization procedure in order to get the remaining model parameters: f_n and φ_n. The criteria for acquiring a proper set of these parameters is to utilize the minimization of the L_p-norm, which is addressed as L_p-norm method (LPNM) in [19, 20].

Turning back to the expressions (9a)–(9d) and referring to the discussion on the expressions (4a)–(4d) in Section 2, we find that (9a) and (9b) are just special cases of (9c) and (9d), respectively, when $\chi = 0$. Note also that φ_n does not appear in (9a) and (9b). These observations incite us to first optimize f_n by minimizing the following error norm ($p = 2$):

$$E_{f_n} = W_1 \left[\int_0^{\tau_{max}} \left| r_{\mu_i \mu_i}(\tau) - \tilde{r}_{\mu_i \mu_i}(\tau) \right|^2 d\tau \right]^{1/2} + W_2 \left[\int_0^{\tau_{max}} \left| r_{\mu_1 \mu_2}(\tau) - \tilde{r}_{\mu_1 \mu_2}(\tau) \right|^2 d\tau \right]^{1/2} , \tag{10}$$

where $i = 1, 2$, W_1 and W_2 are real-valued weighting factors which have to be chosen properly by the user. The constant τ_{max} defines an adequate delay interval $[0, \tau_{max}]$ in which the approximation of $\tilde{r}_{\mu_i \mu_i}(\tau)$ and $\tilde{r}_{\mu_1 \mu_2}(\tau)$ is of interest. For simplicity, we have chosen $\tau_{max} = 0.05$ s in this paper. The optimized set of f_n will be obtained by applying an optimization approach to E_{f_n}.

If we substitute the obtained set of f_n into (9c) and (9d), it then follows that the final parameters φ_n can be obtained by the minimization of the following error norm:

$$E_{\varphi_n} = W_3 \left[\int_{-\chi_{max}}^{\chi_{max}} \int_0^{\tau_{max}} \left| r_{\mu_i \mu_i'}(\tau, \chi) - \tilde{r}_{\mu_i \mu_i'}(\tau, \chi) \right|^2 d\tau d\chi \right]^{1/2} + W_4 \left[\int_{-\chi_{max}}^{\chi_{max}} \int_0^{\tau_{max}} \left| r_{\mu_1 \mu_2'}(\tau, \chi) - \tilde{r}_{\mu_1 \mu_2'}(\tau, \chi) \right|^2 d\tau d\chi \right]^{1/2} , \tag{11}$$

where $i = 1, 2$, W_3 and W_4 are again representing weighing factors, χ_{max} means the maximum frequency hop size which should be larger than or equal to the coherence bandwidth of the channel. It has been mentioned in [11] that the coherence bandwidth of practical cellular systems is on the order of 1–2 MHz, which allows us to address the range of χ from -2.5 MHz to 2.5 MHz, and thus, χ_{max} =2.5 MHz. Then, by applying a numerical optimization approach to E_{φ_n}, we can obtain an optimized set of the model parameters φ_n.

V. PERFORMANCE EVALUATION

In this section, we analyze the performance of the proposed FH channel simulator by comparing the correlation properties of the simulation model [see (9a)–(9d)] with those of the analytical model [see (4a)–(4d)]. Due to the fact that some model parameters (f_n and φ_n), obtained by the exploited LPNM method, are not available in a closed-form, it is impossible to evaluate the convergency of the simulation model to the analytical model when the number of parameters tends to infinity. However, we can study the inevitable degradation effects of the simulation model based on a finite number of sinusoids. For the proposed simulator, $N = 40$ is selected as a good compromise between the model's precision and complexity.

1) Comparison of $\tilde{r}_{\mu_i\mu_i}(\tau)$ with $r_{\mu_i\mu_i}(\tau)$: As an example, Fig. 1 impressively shows the excellent accordance between $\tilde{r}_{\mu_1\mu_1}(\tau)$ and $r_{\mu_1\mu_1}(\tau)$ for the given number of sinusoids. In order to check the validity of our analytical expressions, the simulation result is also illustrated in this figure, which is completely complied with the result of our simulation model.

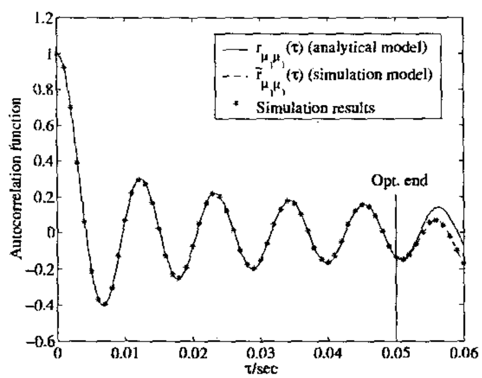


Fig. 1: Autocorrelation function $r_{\mu_1\mu_1}(\tau)$ (analytical model) in comparison with $\tilde{r}_{\mu_1\mu_1}(\tau)$ (simulation model, $N = 40$) for $f_{max} = 91$ Hz and $\sigma_0^2 = 1$.

2) Comparison of $\tilde{r}_{\mu_1\mu_2}(\tau)$ with $r_{\mu_1\mu_2}(\tau)$: Equation (4b) states that the inphase and quadrature components of the analytical model are uncorrelated. For its counterpart of the simulation model, i.e., $\tilde{r}_{\mu_1\mu_2}(\tau)$, we find that there unavoidably exists a correlation, as can be seen from Fig. 2. But $\tilde{r}_{\mu_1\mu_2}(\tau)$ is so small in the optimization range that the correlation can be neglected in practice.

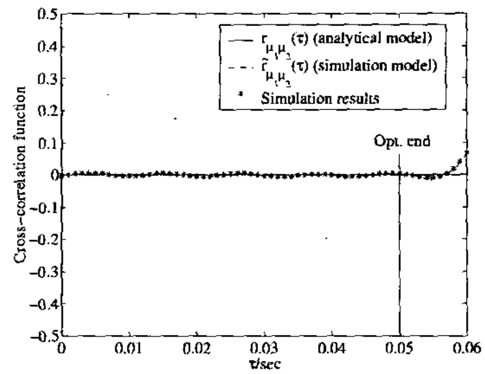


Fig. 2: Cross-correlation function $r_{\mu_1\mu_2}(\tau)$ (analytical model) in comparison with $\tilde{r}_{\mu_1\mu_2}(\tau)$ (simulation model, $N = 40$) for $f_{max} = 91$ Hz and $\sigma_0^2 = 1$.

3) Comparison of $\tilde{r}_{\mu_i\mu_i'}(\tau, \chi)$ with $r_{\mu_i\mu_i'}(\tau, \chi)$: Based on the COST 207 RA profile [18], the numerical results of $\tilde{r}_{\mu_1\mu_1'}(\tau, \chi)$ and $r_{\mu_1\mu_1'}(\tau, \chi)$ are shown in Figs. 3(a) and 3(b), respectively. The obtained error norm is also presented in Fig. 3(b). It can be observed that the quality of the achieved approximation is pretty good for $N = 40$. To emphasize this aspect, we also give in Fig. 4 the analytical results of $\tilde{r}_{\mu_1\mu_1'}(0, \chi)$ and $r_{\mu_1\tilde{\mu}_1'}(0, \chi)$, which represent the cross-correlation functions $\tilde{r}_{\mu_1\mu_1'}(\tau, \chi)$ and $r_{\mu_1\mu_1'}(\tau, \chi)$ along the χ-axis, respectively.

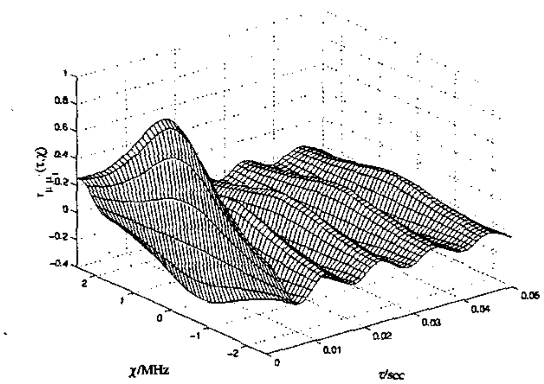
4) Comparison of $\tilde{r}_{\mu_1\mu_2'}(\tau, \chi)$ with $r_{\mu_1\mu_2'}(\tau, \chi)$: As shown in Figs. 5(a) and 5(b), excellent approximation results for $\tilde{r}_{\mu_1\mu_2'}(\tau, \chi) \approx r_{\mu_1\mu_2'}(\tau, \chi)$ can be achieved even for a moderate value of N. Concerning the behaviour of $r_{\mu_1\mu_2'}(\tau, \chi)$ and $\tilde{r}_{\mu_1\mu_2'}(\tau, \chi)$ along the χ-axis, we compare $r_{\mu_1\mu_2'}(0, \chi)$ with $\tilde{r}_{\mu_1\mu_2'}(0, \chi)$ in Fig. 6.

Note that Fig. 4 and Fig. 6 are of great importance to choose the appropriate frequency separation ensuring the uncorrelatedness between hops. If we choose as a measure of uncorrelatedness, the correlation which is less than or equal to 0.5, we see that this occurs when the absolute value of χ is larger than 1.47 MHz, which can be employed to set up the frequency hop size in FH systems with the specified RA profile.

VI. CONCLUSION

In this paper, we have proposed a novel deterministic channel simulator for the emulation of FH Rayleigh fading channels. Some parameters were determined by using a *numerical optimization method*. The performance analysis of our simulation model with a limited number of parameters was also discussed and it turned out that we can place enough confidence on the proposed simulator in the approximation of the correlation properties of the underlying analytical model with acceptable computational efforts. Therefore, this model is expected to play a significant role in providing good precision and low complexity system design for practical FH mobile communication systems.

(a)



(b)

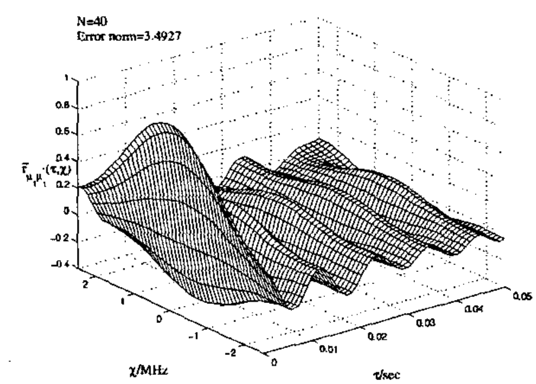


Fig. 3: Cross-correlation function $r_{\mu_1\mu_1'}(\tau,\chi)$ for the COST 207 RA profile ($\alpha = 0.1086$ μs, $f_{max} = 91$ Hz, $\sigma_0^2 = 1$): (a) $r_{\mu_1\mu_1'}(\tau,\chi)$ (analytical model) and (b) $\tilde{r}_{\mu_1\mu_1'}(\tau,\chi)$ (simulation model, $N = 40$).

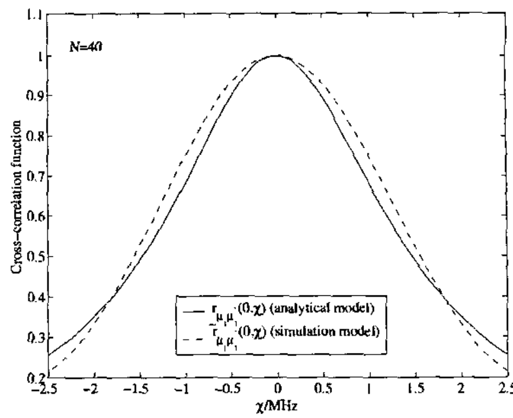
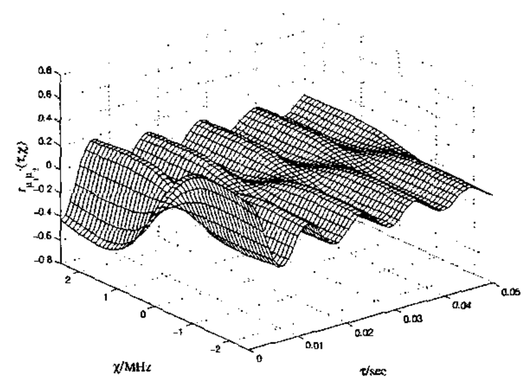


Fig. 4: Cross-correlation function $r_{\mu_1\mu_1'}(0,\chi)$ (analytical model) in comparison with $\tilde{r}_{\mu_1\mu_1'}(0,\chi)$ (simulation model, N=40) for the COST 207 RA profile ($\alpha = 0.1086$ μs, $f_{max} = 91$ Hz, $\sigma_0^2 = 1$).

(a)



(b)

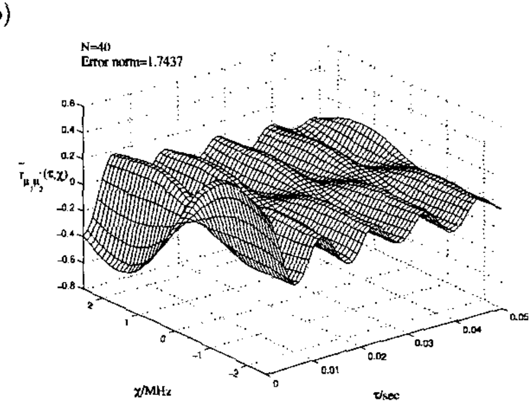


Fig. 5: Cross-correlation function $r_{\mu_1\mu_2'}(\tau,\chi)$ for the COST 207 RA profile ($\alpha = 0.1086$ μs, $f_{max} = 91$ Hz, $\sigma_0^2 = 1$): (a) $r_{\mu_1\mu_2'}(\tau,\chi)$ (analytical model) and (b) $\tilde{r}_{\mu_1\mu_2'}(\tau,\chi)$ (simulation model, $N = 40$).

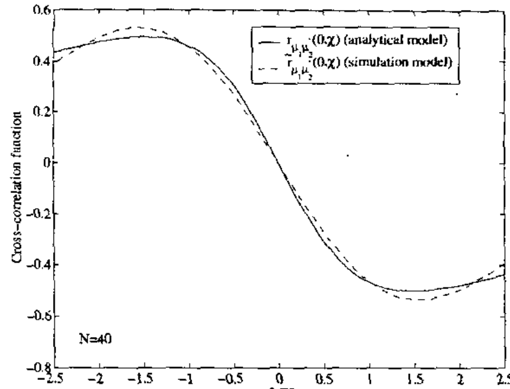


Fig. 6: Cross-correlation function $r_{\mu_1\mu_2'}(0,\chi)$ (analytical model) in comparison with $\tilde{r}_{\mu_1\mu_2'}(0,\chi)$ (simulation model, N=40) for the COST 207 RA profile ($\alpha = 0.1086$ μs, $f_{max} = 91$Hz, $\sigma_0^2 = 1$).

REFERENCES

[1] C. Carneheim, S. O. Jonsson, M. Ljungberg, M. Madfors and J. Näslund, "FH-GSM frequency hopping GSM," in *Proc. IEEE 44th Veh. Technol. Conf.*, Sweden, June 1994.

[2] G. W. Tunnicliffe, A. Sathyendran and A. R. Murch, "Performance improvement in GSM networks due to slow frequency hopping," in *Proc. IEEE 47th Veh. Technol. Conf.*, Pheonix, Arizona, USA, May 1997.

[3] S. Chennakeshu, A. A. Hassan, J. B. Anderson and B. Gudmundson, "Capacity analysis of a TDMA-based slow-frequency-hopped cellular system," *IEEE Trans. Veh. Technol.*, vol. 45, no. 3, pp. 531–542, August 1996.

[4] A. Sathyendran and P. J. Smith, "A theoretical study of the performance improvement in GSM networks due to slow frequency hopping," in *Proc. IEEE 48th Veh. Technol. Conf.*, Ottawa, Ontario, Canada, May 1998.

[5] T. T. Nielsen, J. Wigard, P. H. Michaelsen and P. Mogensen, "Slow frequency hopping solutions for GSM networks of small bandwidth," in *Proc. IEEE 48th Veh. Technol. Conf.*, Ottawa, Ontario, Canada, May 1998.

[6] S. H. Kim and S. W. Kim, "Frequency-hopped multiple-access communications with multicarrier on-off keying in Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 48, no. 10, pp. 1692–1701, October 2000.

[7] T. C. Wu, C. C. Chao and K. C. Chen, "Capacity of synchronous coded DS SFH and FFH spread-spectrum multiple-access for wireless local communications," *IEEE Trans. Commun.*, vol. 45, no. 2, pp. 200–212, February 1997.

[8] S. Tomisato, K. Fukawa and H. Suzuki, "Coherent frequency hopping multiple-access (CFHMA) with multiuser detection for mobile communication systems," *IEEE Trans. Veh. Technol.*, vol. 49, no. 2, pp. 531–539, March 2000.

[9] C. H. Park, Y. H. You, J. H. Paik, M. C. Ju and J. W. Cho, "Channel estimation and DC-offset compensation schemes for frequency-hopped bluetooth networks,", *IEEE Trans. Commun. Letters*, vol. 49, no. 2, pp. 531–539, January 2000.

[10] M. Chiani, E. Agrati and O. Andrisano, "An analytical approach to evaluate service coverage in slow frequency-hopping mobile radio systems," *IEEE Trans. Commun.*, vol. 49, no. 8, pp. 1447–1456, August 2001.

[11] Z. Kostic, M. Ivana and X. D. Wang, "Fundamentals of dynamic frequency hopping in cellular systems," *IEEE J. on Selected Areas in Communications*, vol. 19, no. 11, pp. 2254–2266, November 2001.

[12] U. Lambrette, S. Fechtel and H. Meyer, "A frequency domain variable data rate frequency hopping channel model for the mobile radio channel,", in *Proc. IEEE 47th Veh. Technol. Conf.*, Pheonix, Arizona, USA, May 1997.

[13] T. Klingenbrunn and P. Mogensen, "Modeling frequency correlation of fast fading in frequency hopping GSM link Simulations," in *Proc. IEEE 50th Veh. Technol. Conf.*, Amsterdam, The Netherlands, September 1999.

[14] C. X. Wang and M. Pätzold, "A novel stochastic slow frequency hopping simulation model for Rayleigh fading channels," in *Proc. IEEE 4th Wireless Personal Multimedia Communications (WPMC'01)*, Aalborg, Denmark, September 2001.

[15] S.O. Rice, "Mathematical analysis of random noise," *Bell Syst. Tech. J.*, vol. 23, pp. 282–332, July 1944.

[16] S.O. Rice, "Mathematical analysis of random noise," *Bell Syst. Tech. J.*, vol. 24, pp. 46–156, January 1945.

[17] W.C. Jakes, Ed., *Microwave Mobile Communications.* New Jersey: IEEE Press, 1993.

[18] COST 207, "Digital land mobile radio communications,", *Office for Official Publications of the European Communities* Final Report, Luxemburg, 1989.

[19] M. Pätzold, U. Killat, F. Laue and Y. Li, "On the statistical properties of deterministic simulation models for mobile fading channels,", *IEEE Trans. Veh. Technol.*, vol. 47, no. 1, pp. 254-269, February 1998.

[20] M. Pätzold, *Mobile Fading Channels*, John Wiley & Sons, Chichester, 2002.